A RARE GAS OPTICS-FREE ABSOLUTE PHOTON FLUX AND ENERGY ANALYZER TO PROVIDE ABSOLUTE PHOTOIONIZATION RATES OF INFLOWING INTERSTELLAR NEUTRALS

(NASA Grant No. NAGW-2677)

Period of Performance: December 1, 1991 to May 31, 1994

Submitted by:
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November 1994

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FINAL REPORT

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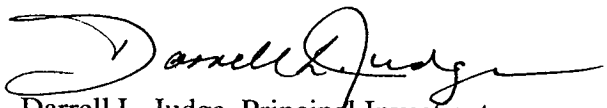
Submitted to:

Attention: Dr. Vernon Jones
Cosmic and Heliospheric Physics Discipline
Space Physics Division, Code SS
National Aeronautics and Space Administration
Washington, DC 20546-0001

Submitted by:



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I. INTRODUCTION

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II. SUMMARY OF ACCOMPLISHMENTS

A. Work Presented at Scientific Conferences

The following is a list of contributed and invited papers which acknowledge the NASA grant.

1. M. D. Daybell, M. A. Gruntman, D. L. Judge and J.A.R. Samson, "A rare gas optics-free absolute EUV photon spectrometer for solar system studies", Proc. SPIE 1745, p 149 (1992).

2. M. D. Daybell, M. A. Gruntman, D. L. Judge and J.A.R. Samson, "An Optics-Free Absolute EUV Photon Spectrometer for Solar System Studies Utilizing Photoelectron-Photoion Coincidence", Eos, Trans., AGU, 73 (supp.) p. 430 (1992).

3. M. D. Daybell, M. A. Gruntman, J. R. Hoffman .and D. L. Judge, "An Optics Free Spectrometer for Solar System EUV Studies", Eos, Trans., AGU,74 (supp.) p. 224 (1993).

4. D.L. Judge, "An Optics-Free Spectrometer (OFS) for the Extreme Ultra-Violet (EUV)", presented at the 8th National Conference on Synchrotron Radiation Instrumentation, Gaithersburg, Maryland August 23-26, 1993

B. Work Presented in Scientific Journals

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3. D. L. Judge, M. D. Daybell, J. R. Hoffman, M. A. Gruntman, H. S. Ogawa, J.A.R. Samson, "An optics free spectrometer for the extreme ultraviolet", Nucl. Inst. Meth. A 347 p. 472 (1994).

III . COPIES OF PUBLICATIONS WHICH ACKNOWLEDGE NASA GRANT NAGW-2677

A rare gas optics-free absolute EUV photon spectrometer for solar system studies

M. D. Daybell, M. A. Gruntman and D. L. Judge

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ABSTRACT

We have developed a prototype spectrometer for space applications which require long term absolute EUV photon flux measurements. In this recently developed spectrometer, the energy spectrum of the incoming photons is transformed directly into an electron energy spectrum by taking advantage of the photoelectric effect in one of several rare gases at low pressures. Using an electron energy spectrometer operating at a few eV, and followed by an electron multiplying detector, pulses due to individual electrons are counted. The overall efficiency of this process is essentially independent of gain drifts in the signal path, and the secular degradation of optical components which is often a problem in other techniques is avoided.

1. INTRODUCTION

Research programs within planetary, cometary, and heliospheric sciences ultimately require absolute solar flux data in the highly variable extreme ultraviolet (EUV) spectral region. The scientific programs have matured to the point where flux estimates which currently may be wrong by a factor of two or more are no longer acceptable. Both planned planetary observations and ongoing missions require absolute solar flux data which have not been compromised by degradable optics and detectors. Despite myriads of observations, the absolute solar UV flux and its variation throughout the wavelength region below 1000 Å has not been well established for detailed aeronomical and astrophysical studies. The susceptibility of previously flown solar instrumentation to solar driven degradation of both the optics and detectors make it difficult to separate true solar variability from changes in the instrumentation sensitivity.

The goal of this work is to present an alternative way to measure the solar EUV spectrum, a method with a minimum of degradable optical (hence "optics-free") elements. Such an approach, described by Judge et. al.[1] should eventually result in the development of a new generation of highly stable and reliable spectrometers for monitoring the solar EUV radiation spectrum on a continuous basis. The idea of the technique was first proposed by Samson[2] and uses photoionization of gas target atoms to convert an EUV photon spectral distribution into an energy distribution of the photoelectrons, which is finally measured. Though this technique has been applied in laboratory studies, the feasibility of its implementation in space instrumentation has yet to be demonstrated. Specific conditions of space applications pose stringent requirements on instrument characteristics, particularly its speed and consumption of the expendable target gas.

Different approaches are possible to measure the photoelectron energy distribution. A photoelectron spectrometer based on measurement of the photoelectron current is hardly acceptable because of its low sensitivity. Attempts to increase photoelectron collection by introducing magnetic fields and using diffusion of electrons in the gas face serious problems of magnetic field inhomogeneities and electron inelastic collision processes (Mishchenko et. al.[3]). The overall weight of an instrument based on such an approach practically precludes its application in space. The only feasible way seems to be to use an electron energy analyzer and count individual electrons (Judge et. al.[1], Bendich et. al.[4]). To increase the instrument's sensitivity, and consequently its speed, continues to be a challenging task. Another challenge is to eliminate the stray electron and photon background count rate. This could be achieved by requiring coincident detection of the positive photoions. The aim of this work is to give a comprehensive view of the photoelectron energy analysis technique, to demonstrate its feasibility as a photon spectrometer, and to discuss some inherent advantages and disadvantages of various ways of implementing it.

Figure 2 shows some of the elements that might be found in an optics-free spectrometer (OFS).

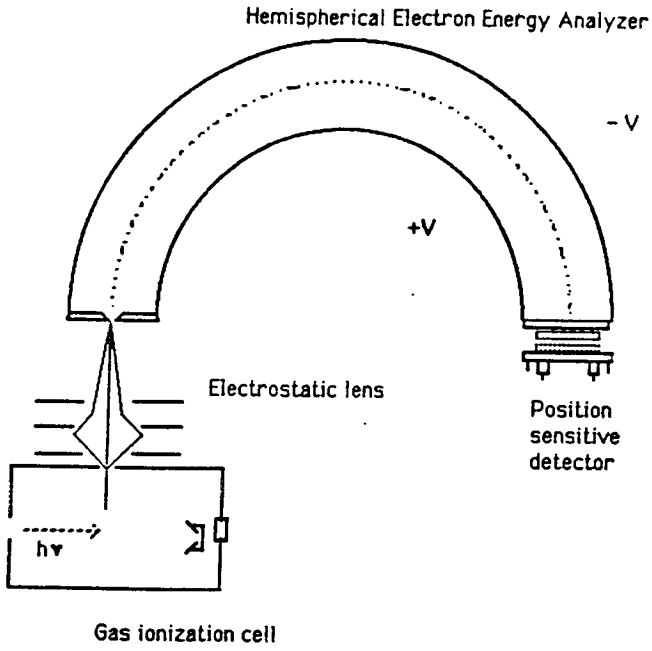


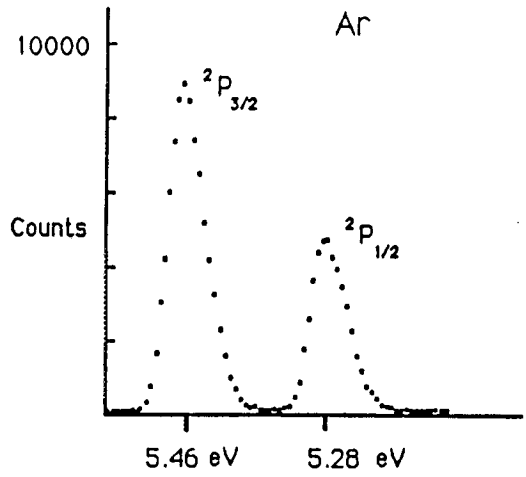
Fig. 2 Schematic diagram of an OFS using an electron lens, a spherical electrostatic electron energy analyzer and a position sensitive array detector.

3. PERFORMANCE OF SOME SIMPLE OPTICS-FREE SPECTROMETERS

Imagine first that the lens is omitted, the entrance slit of the energy analyzer is placed just outside the hole in the wall of the ionization cell, and a simple exit slit backed by an electron counter is substituted for the position sensitive detector. An example of a spectrum obtained using a dc discharge in argon (Ar II) as the undispersed EUV source incident on the ionization cell of just such an OFS in our lab at the University of Nebraska appears in Figure 3. (The analyzer used consisted of a sector of a hemisphere, not the usual complete hemisphere.) The cell also contained argon, and as mentioned earlier, the energy and wavelength of each spectral line is obtained by adding the ionization energy of argon, 15.77eV or 15.95eV (for the members of the ion doublet) to the electron energy. The plot shows the number of electrons counted at each step in the electron energy (notice the scale change near 3 eV) as a function of electron energy. Prominent lines are marked with their wavelength in angstroms. The curved base line represents the true base line, and indicates the effect of scattered electrons, reminiscent of the effect of scattered light in a conventional optical monochromator.

For comparison, Figure 4 shows an Ar II spectrum obtained using an optical monochromator (the source was a duoplasmatron). The resolution is no better than the OFS, although the noise level using this weak source and simple geometry is somewhat higher for the OFS.

For space applications, it will be necessary to utilize OFS configurations that can gather EUV spectra in reasonable times (a half-hour or less) . An electron energy analyzer with a position-sensitive detector in its image plane (so that it becomes an electron spectrometer) can acquire data at many energies at once. The true hemispherical electron analyzer appears to be able to utilize a position-sensitive detector more effectively than some of the other geometries, and may be less affected by scattered electrons than the CMA. We have run a few tests on such an analyzer (but without the position-sensitive detector) , and show in Figure 5 its response to a monochromatic light source, the strong He line at 584 Å. The ionization cell was filled with argon, and the two ionization states of argon produce the two lines shown. The statistical weight of the 3/2 state is twice that of the 1/2 state, and the relative height of the two lines reflects this quite closely. The known ionization energy difference is 0.178 eV and the electron energy at which the two lines should occur is marked on the energy axis. The dwell time for each point was 10 seconds. (Two photon lines near 584Å that differ in energy by 0.178eV would differ in wavelength by 4.9Å. The resolution is clearly much higher than this.)



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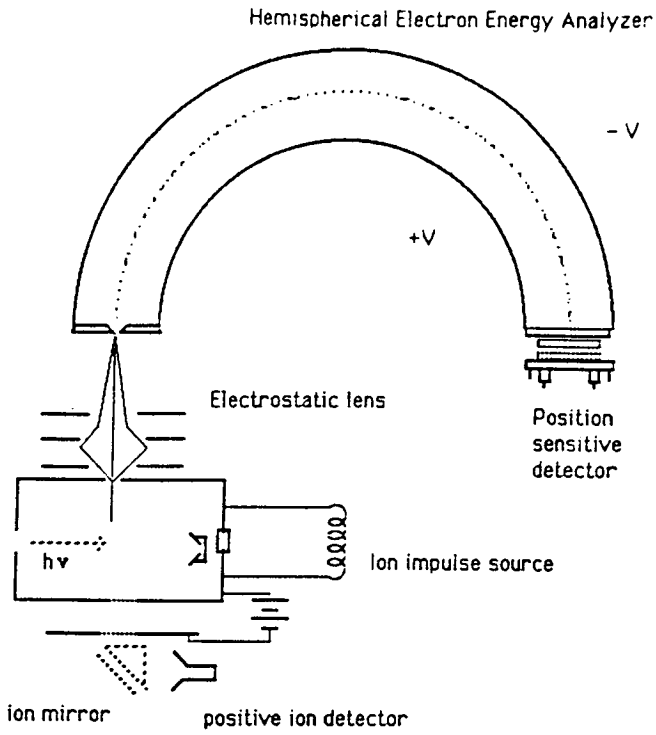
In each case discussed above, the potential difference between the capacitor plates of the analyzer was held constant, fixing the analyzer pass energy at 2 or 3 eV, and the electron energy was scanned by varying the potential difference between the rare gas ionization cell and the analyzer. This has the desirable effect of holding the energy resolution constant, leading to excellent fractional energy resolution at high energies. On the other hand, the entrance slit of the electron analyzer combined with the housing of the ionization cell form a basic electron lens, which must obey the laws of electron optics, which tell us that if the lens slows the electrons down, a smaller fraction of the photoelectrons leaving the object space of the lens will fit into the fixed acceptance solid angle of the analyzer, so the transmission of the system will drop as the potential retarding the electrons is increased. Another obvious approach is to keep this retarding potential constant, but scan the voltages on the capacitor plates of the analyzer. The fractional energy resolution then is fixed, but the transmission at high energies is better. This tradeoff is desirable in many space applications.

4. DESIGN FEATURES OF A RECENT OPTICS-FREE SPECTROMETER

In choosing the design parameters for an OFS , it is helpful to notice that the mean free paths of photoelectrons and of atoms in a rare gas are roughly comparable, while that of the photons is considerably longer. Once we choose a gas pressure for our ionization cell, the dimension of the cell must be limited to a fraction of the electron mean free path if we are to get the photoelectrons out. This in turn limits the cross sectional area of the window the cell can open to the sun. Since the number of detectable photoelectrons produced depends on the product of the pressure, the area of the photon beam, the size of the slit through which electrons exit the cell, and the acceptance solid angle of the electron analyzer, if we scale all three dimensions of the spectrometer, keeping the solid angle constant, and dropping the pressure to keep the mean free path in scale, the counting rate will scale approximately as the square of the dimensions. The loss rate of target gas out the window to the sun will increase only linearly with the scale, since we are in the molecular flow regime. A rough estimate indicates that a 100 cm^2 window would support several spectra per day for a year with a one liter gas supply initially at a few hundred psi. The resulting OFS system would be rather large. Our present system has a window of 2 cm^2 and its analyzer is about 14 cm across.



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A little ingenuity may be required to apply the ion coincidence idea to a few of the most efficient OFS designs, but its potential virtues make it worth investigating for some applications, and would lead to a well-characterized OFS well suited to providing highly reliable absolute flux data in the extreme ultraviolte spectral region.

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6. REFERENCES

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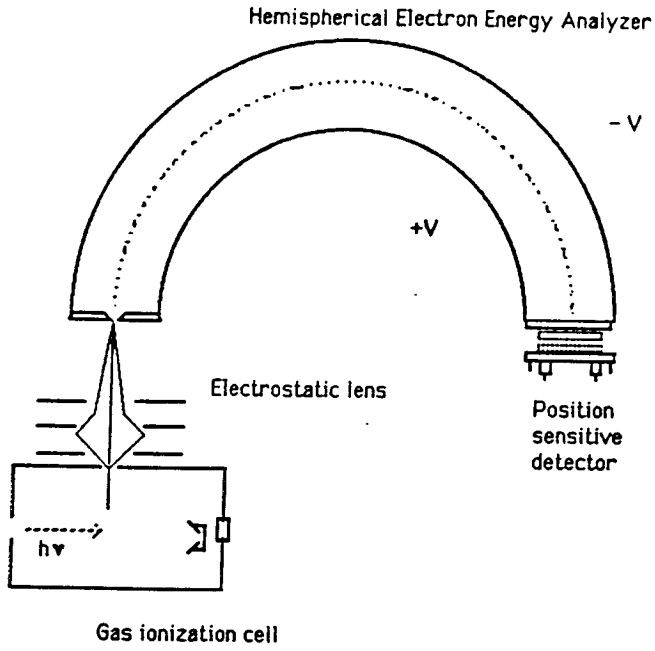

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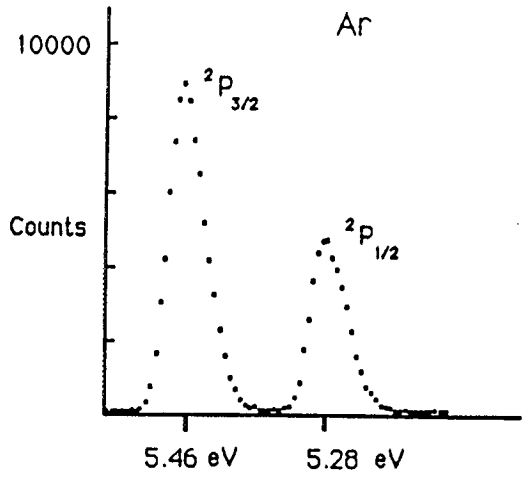

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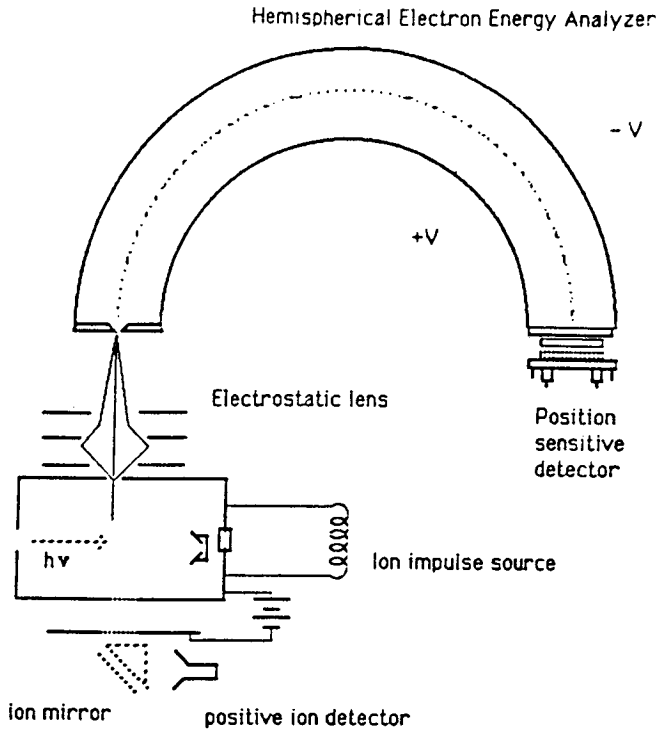

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Rare-gas optics-free stable extreme-ultraviolet photon spectrometer for solar system studies

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Abstract. We have developed a prototype spectrometer for space applications that require long-term stable EUV photon flux measurements. In this recently developed spectrometer, the energy spectrum of the incoming photons is transformed directly into an electron energy spectrum by taking advantage of the photoelectric effect in one of several rare gases at low pressures. Using an electron energy spectrometer operating at a few electron volts, and followed by an electron multiplying detector, pulses due to individual electrons are counted. The overall efficiency of this process is essentially independent of gain drifts in the signal path, and the secular degradation of optical components that is often a problem in other techniques is avoided.

Subject terms: atmospheric remote sensing; EUV spectrometers; space instrumentation.

Optical Engineering 33(2), 445–450 (February 1994).

1 Introduction

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Paper MI-040 received April 1, 1993; revised manuscript received Aug. 19, 1993; accepted for publication Aug. 30, 1993. This paper is a revision of a paper presented at the SPIE conference on Instrumentation for Planetary and Terrestrial Atmospheric Remote Sensing, July 1992, San Diego, Calif. The paper presented there appears (unrefereed) in SPIE Proceedings Vol. 1745.

2 Optics-Free EUV Spectrometers

The strategy of using a rare-gas optics-free absolute EUV photon spectrometer for solar system studies takes advantage of a novel technique first presented by Samson.[2] Using this method, it became possible to monitor the absolute spectral irradiance of a UV light source and to determine accurately the values of molecular parameters requiring a knowledge of the absolute flux from such sources. This same capability to measure the absolute flux over periods longer than a year promises to be very useful in time and wavelength resolved EUV solar flux surveys below 1000 Å.

The optics-free spectrometer (OFS) instrument actually performs its spectroscopy on electrons using an electron energy analyzer (Fig. 1). This analyzer transfers the spectral distribution of the light source, via photoionization of a stable atomic gas (rare gas), into an electron energy distribution through the Einstein equation $h\nu = I + E_e$, where $h\nu$ is the energy of the photons, I is the ionization potential of the rare-gas atom, and E_e is the energy of the ejected photoelectrons. Thus, in the case of photoionization of helium, for example, a discrete electron energy is produced for each discrete wavelength emitted by the source. If the other rare gases are used, two discrete electron energy groups are produced for each discrete wavelength. These two groups correspond to the creation of the ion in its $^2P_{3/2}$ or $^2P_{1/2}$ state. Because a gas with a known and, more importantly, time-independent photoionization cross section is used, the analyzer is capable of providing stable values of the absolute spectral irradiance of the light source. It is only necessary to maintain the geometry constant, know the gas pressure, and use a reliable electron counter, for example, one of the channeltrons or microchannel plate assemblies of the type used in earlier long-duration space missions.

The principle of operation is as follows: The number of electrons detected per second $N(\lambda)$ depends on the number of photons per second JA passing through the effective area A of the ionization cell visible to the electron energy analyzer, the effective thickness t of the cell, the number density n of the target gas, its photoionization cross section σ for the angle where the analyzer's entrance aperture is located, and the solid angle $\Delta\Omega$ subtended by this aperture at the cell. An additional factor η describes the transmission of the electron analyzer and the efficiency of the detector.

Then,

$$N(\lambda) = JA\sigma nt\Delta\Omega\eta \ .$$

This can be expressed as

$$N(\lambda) = C(\lambda)J(\lambda)\sigma(\lambda)n \ ,$$

where

$$C(\lambda) = At\Delta\Omega\eta$$

is an instrumental constant that can be calculated from the geometry or, more often, determined in a calibration measurement. If the absolute radiant energy of the source used in the calibration is known, this measurement will transform the OFS spectrometer into a secondary standard; if not, $C(\lambda)$ can be expressed in relative units. Later, we discuss an ion-electron coincidence counting technique that makes it possible to monitor the stability of $C(\lambda)$ after the experiment is in place.

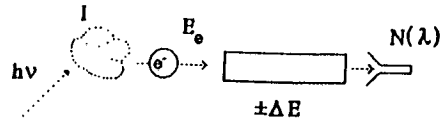

Fig. 1 The OFS concept.

A variety of designs exist for electron energy analyzers. The requirements here differ from those widely used in EUV and x-ray surface studies, solid state physics research, electron microscopy, and chemical analysis in that we have a large uniform and diffuse source, but a high collection efficiency for electrons produced in the source volume is still required. The electron flux is low, so that space charge effects can be ignored. The energy resolution required is not excessive. We do, however, have to scan more than one decade of electron energy and must usually work in the presence of an unavoidable background of neutral rare-gas atoms that come through the exit slit of the photoionization cell along with the electrons.

A schematic view of our laboratory OFS is shown in Fig. 2. The EUV photons enter from the right through a series of slits ahead of a small ionization volume, or gas box, located above an electron lens. Behind the gas box, on the left, is a light trap. The ion-coincidence accessory above the gas box will be described later. The flow of target gas out of the gas box region is constrained by the slits along the incoming photon beam and by the small slit on the bottom of the gas box connecting it with the electron lens. The gas pressure is 10 to 50 mTorr and gas consumption is small. The electron lens allows escaping target gas to be removed from the path of the electrons being analyzed.

Photoelectrons exiting the bottom slit are imaged on the entrance slit of a 180-deg hemispherical plate electrostatic energy analyzer, and electrons of the chosen energy come to a focus at its exit slit. After passing through this slit they are detected by a channeltron-style electron multiplier.

The electron energy spectrum is obtained by sweeping the potentials applied to the lens-analyzer system and monitoring the count rate from the channeltron.

3 Performance of Some Simple Optics-Free Spectrometers

Two emission spectra obtained with our OFS are shown in Figs. 3 and 4. The simplest emission spectrum is that of atomic helium shown in Fig. 3. Here, the $n = 2 \rightarrow 1$ (584 Å), $3 \rightarrow 1$ (537 Å), and $4 \rightarrow 1$ (522 Å) transitions are clearly visible. The more complex argon emission spectrum is shown in Fig. 4. Both spectra were obtained using argon as the target gas in which the electron-ion pairs were produced. In the helium spectrum, the 178-meV splitting associated with the two ionization states of the argon target is clearly resolved. (At 584 Å, this splitting is equivalent to 4.9 Å. The resolution is clearly better than this.) The absence of a significant stray electron background should also be noted. We have included a 20× enlargement of this spectrum (Fig. 5). A typical helium spectrum obtained using a representative grating spectrometer is included for comparison (Fig. 6).

To reach the data rates required for shuttle applications, we are planning to add a microchannel plate position-

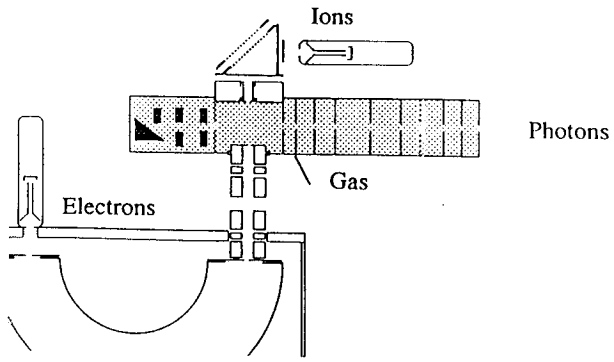

Fig. 2 Schematic diagram of an OFS using an electron lens, a spherical electrostatic electron energy analyzer, and a channeltron electron multiplier. Also included is an optional channel to detect the coincident photo ion.

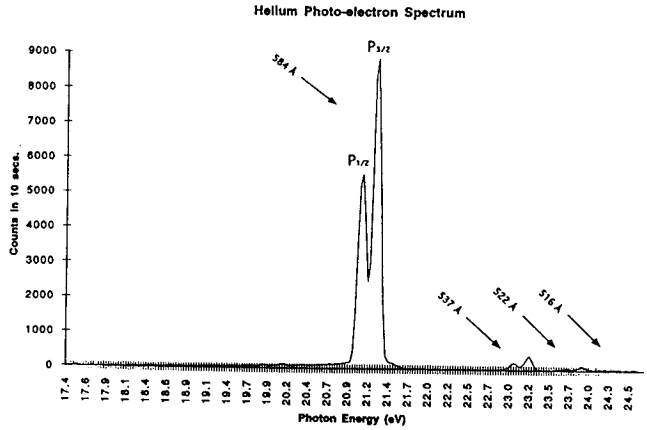

Fig. 3 Electron counts per energy step versus electron energy with an OFS similar to Fig. 2. The EUV source was an undispersed He-I microwave glow discharge. The rare-gas ionization cell contained argon.

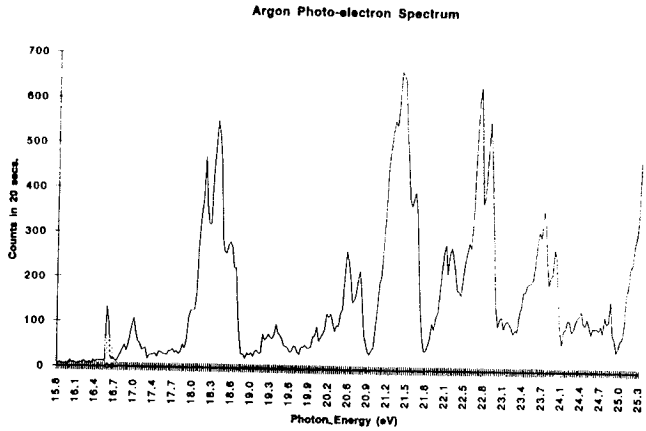

Fig. 4 An OFS spectrum of Ar II. The conditions were the same as for Fig. 3, except that an undispersed Ar-II microwave glow discharge was substituted for the He-I source.

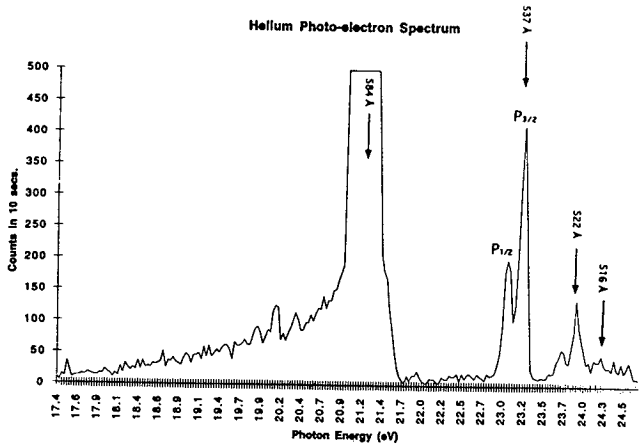

Fig. 5 The He-I OFS spectrum of Fig. 3 expanded vertically by a factor of 20× to better show the weaker elements of the He-I principal resonance series.

sensitive detector at the back focus of the electron energy analyzer, replacing the back slit and the channeltron. In essence, this yields many electron energy channels in parallel and increases the data acquisition rate in direct proportion to the effective number of channels, without increasing the consumption of target gas.

The ion coincidence channel shown above the gas box is an additional enhancement that lets us sweep out and detect the ion created in the same photoionization event that produced the electron. This optional feature allows us to eliminate background events and to monitor the absolute sensitivity of the OFS after it is in service. Implementation of this enhancement will improve the already high quality data shown in Figs. 3 and 4.

One component not shown in the schematic is the magnetic shielding used to screen out the Earth's field. Absence of this shielding is known to restrict the wavelength region of OFS operation to shortward of around 400 Å. We hold the field in our spectrometer to about 1 mG and can operate throughout the rare-gas ionization region ($\lambda < 1022$ Å).

Except for helium, each of the rare gases that might be used as a photoionization target may be left in one of two ionized states with nearly the same energy. This leads to a pair of photoelectron peaks for each incident photon wavelength, as seen in Fig. 3 for an argon target ionized by the 584-Å line from a helium lamp. Using an advanced deconvolution algorithm based on that of Allen and Grimm[6] and taking the "instrument function" to be the experimental response to the sharp isolated 584-Å line, it is possible to transform the output trace of the OFS into a very good replica of the input photon spectrum. This has been done in Figs. 7(a) and 7(b) at two different vertical scales for the resonance series of helium discussed earlier. Notice that the annoying line doubling in the output trace has disappeared. Also, the resolving power appears to have improved significantly.

Another appropriate use for deconvolution is to trade instrument sensitivity for resolving power electronically, as required. A photoelectron spectrometer with relatively high sensitivity, and therefore relatively poor resolution, can gain resolution by scanning through its range more slowly to accumulate the better electron counting statistics required for satisfactory performance of the resolution enhancing algorithm.

Some time ago one of us (Samson) obtained results similar to these with a different electron analyzer geometry, the cylindrical mirror analyzer (CMA), in which the photoelectrons

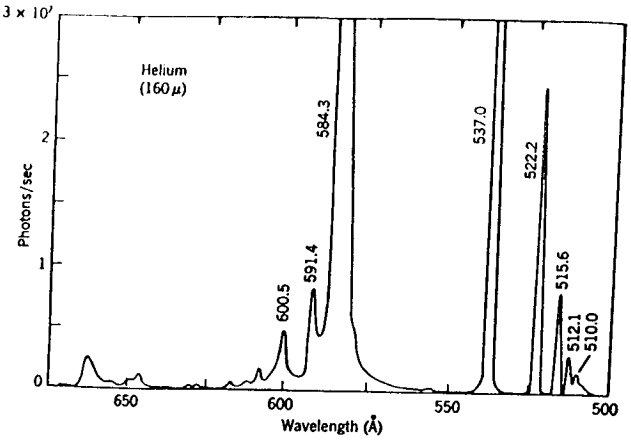

Fig. 6 A He-I spectrum obtained using an optical monochromator (the source was a dc glow discharge[5]).

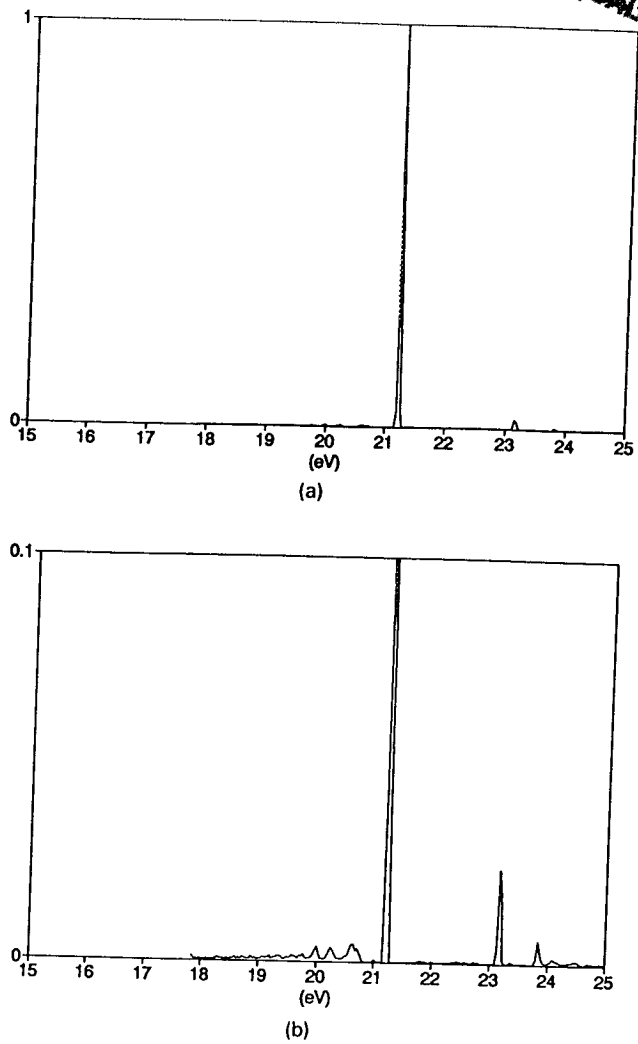

Fig. 7 (a) Deconvolution of the He-I OFS spectrum of Fig. 3 and (b) the same data expanded vertically 20× (compare to Figs. 5 and 6).

created on the axis of a cylindrical capacitor pass outward through an annular slit in the inner plate of the capacitor and then are forced back toward a second identical slit further along the inner cylinder by an electrostatic field between the two plates to refocus on the axis. The results were similar, except that many more electrons were collected and the signal was stronger, but the background due to scattered electrons was more troublesome.

For space applications, it will be necessary to utilize OFS configurations that can gather EUV spectra in reasonable times (a half hour or less). An electron energy analyzer with a position-sensitive detector in its image plane (so that it becomes an electron spectrometer) can acquire data at many energies at once. The hemispherical electron energy analyzer appears to be able to utilize a position-sensitive detector more effectively than some of the other geometries and may be affected less by scattered electrons than the CMA. The scattered electron background present in our OFS (Fig. 5), which uses a hemispherical energy analyzer, is at least an order of magnitude less than in the CMA mentioned earlier.

Two modes are commonly used to scan the measured photoelectron energy over the desired spectral range. In the first mode, the potential difference between the capacitor plates of the analyzer is held constant, fixing the *analyzer* pass energy at 2 or 3 eV, and the electron energy is scanned by varying the potential difference between the rare gas ionization cell and the analyzer. This has the desirable effect of holding the energy resolution constant across the whole energy range, leading to excellent fractional energy resolution at high energies. On the other hand, the entrance slit of the electron analyzer combined with the housing of the ionization cell form a basic electron lens, which must obey the laws of electron optics that tell us that if the lens slows the electrons down, a smaller fraction of the photoelectrons leaving the object space of the lens will fit into the fixed acceptance solid angle of the analyzer; thus, the transmission of the system will drop as the potential retarding the electrons is increased. Another obvious approach is to keep this retarding potential constant, but scan the voltages on the capacitor plates of the analyzer. In this second mode, the fractional energy resolution is fixed, but the transmission at high energies is better. This trade-off is desirable in many space applications.

4 Design Features of a Recent Optics-Free Spectrometer

In choosing the design parameters for an OFS, it is helpful to notice that the mean free paths of photoelectrons and of atoms in a rare gas are roughly comparable, while that of the photons is considerably longer. Once we choose a gas pressure for our ionization cell, the dimension of the cell must be limited to a fraction of the electron mean free path if we are to get the photoelectrons out. This in turn limits the cross-sectional area of the window the cell can open to the sun. Since the number of detectable photoelectrons produced depends on the product of the target gas pressure, the area of the photon beam, the size of the slit through which electrons exit the cell, and the acceptance solid angle of the electron analyzer, if we scale up all three dimensions of the spectrometer, keeping the solid angle constant and dropping the pressure to keep the mean free path in scale, the counting rate will scale approximately as the square of the dimensions. The loss rate of target gas out the window to the sun will increase only linearly with the scale, since we are in the molecular flow regime. A rough estimate indicates that a

100-cm^2 window would support several spectra per day for a year with a 1-L gas supply initially at a few hundred pounds per square inch. The resulting OFS system would be rather large. Our present system has a window of 0.2 cm^2 and its analyzer is about 14 cm across.

One upper limit on the size of the analyzer is the value of the ambient magnetic field, which will reduce its resolution. As a rule of thumb, an analyzer with a resolution of 1%, 10 cm across, can tolerate a field of about 10 mG. Simple Helmholtz coils or magnetic shielding can reduce local fields to this value.

Since the presence of gas atoms in the analyzer, and even more, in the detector degrades performance, an effort must be made to separate these atoms from the electrons as soon as possible using differential pumping. This is the main reason for introducing the electron lens shown in Fig. 2. The lens images the hole in the ionization cell onto the entrance slit of the electron analyzer while allowing atoms escaping from the same hole to be pumped away. The analyzer is nearly enclosed in its own box and may be separately pumped as necessary. With this system, the pressure in the ionization cell is limited by the mean free path of the electrons, or by the rate at which the vacuum pumps the gas out the long entrance tube provided for the photons.

Another function of the electron lens is to image an aperture stop in the object space to an image inside the electron energy analyzer, where it forms a virtual stop to reduce the number of stray electrons. The first and last electrodes of this lens are the ionization cell and the analyzer's entrance slit, respectively, and the lens can be used to scan the energy of the photoelectrons across the pass energy of the analyzer, when this is desirable. The pass energy can also be scanned and since all electrode potentials are interfaced to a CAMAC system, we have computer-controlled resolution as well as energy and can trade off resolution for counting rate as needed. The electron lens as well as the interior of the ionization cell and the electron analyzer have been coated with colloidal graphite dissolved in isopropanol to reduce contact potential effects and cut down on electron charging and stray light scattering.

An ionization-type pressure gauge based on radioactive tritium[7] is used to monitor the pressure in the photoionization cell. The pressure signal is read out by a digital electrometer. This design has served us well for many years.

A modular channeltron/high-voltage-supply/pulse amplifier (Amptektron, Amptek Inc., Bedford, Mass.) serves as the electron detector. A resistive anode behind a stack of microchannel plates forms a position-sensitive detector that can replace the Amptek unit when needed.

In spite of the remarkably good performance of the OFS elements examined so far, some problems remain that have encouraged us to look at an enhancement of the basic strategy. Some stray electron background is still present and it would be useful to have some way to check on the stability of the electron detector. It would also be possible to cover a wide range of photon wavelengths at once if a mixture of rare gases could be accommodated in the ionization cell. For example (see Table 1), a mixture of He and Xe would allow the whole range from 157 to 1022 Å to be covered without complications from double photoionization.

Many of these challenges can be largely eliminated by implementing an ion coincidence technique that will now be described. In the center of the top of the gas box in Fig. 2 is an additional aperture insulated from the gas box. This aperture is cut in a disk forming the bottom of a short metal cylinder and permits the positive ion left behind by the photoelectric event described earlier to be detected. A large voltage pulse (~500 V) can be imposed on this cylinder in such a way as to apply an impulse to the ion directed toward the aperture. This pulse will be triggered only by the arrival of a photoelectron at the electron detector discussed earlier, which will occur on the order of 100 ns after the photoionization event. Beyond the aperture, a constant electric field (~6 kV/cm) accelerates the ion toward an electrostatic mirror (of wire grids), which reflects the ion into a detector (a channeltron is shown). A properly delayed coincidence between the output of the ion detector and that of the electron detector is required for a count to be considered valid. The electrostatic mirror serves to isolate the ion detector from the gas cell and to allow lower gas pressures at this detector, for which another Amptek module modified to collect positive ions can be used.

Table 1 Parameters of the rare gases.

gas	shell	Z	ionization potential (eV)		$\lambda_{threshold}$ (Å)	
			single	double	single	double
He	1s	2	24.580	78.980	504.39	156.98
Ne	2p	10	21.55	62.62	575.1	198.0
Ar	3p	18	15.77	43.39	786.2	285.7
Kr	4p	36	13.99	38.55	886.2	321.6
Xe	5p	54	12.13	33.3	1022	372

With this scheme, the coincidence counting rates will be lower than those described earlier, since some photo ions will be missed, and the gas target pressure will be lower with the ion aperture installed. But any change in the efficiency of either detector will show up as a relative change in the individual detectors' count rates and the coincidence rate, the stray electron background will be eliminated, and, by requiring different delay times between the coincidences, the time of flight of the ion can be selected, thus determining which species of rare-gas ion it is.

A little ingenuity may be required to apply the ion coincidence idea to a few of the most efficient OFS designs, but its potential virtues make it worth investigating for some applications and would lead to a well-characterized OFS well suited to providing highly reliable absolute flux data in the EUV spectral region.

Acknowledgments

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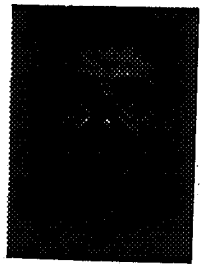
Melvin D. Daybell received a BS from New Mexico State University and a PhD in physics from the California Institute of Technology. He became a physics professor at the University of Southern California in 1968 and joined its Space Science Center in 1991 to develop the optics-free EUV spectrometer.

Michael A. Gruntman: Biography and photograph appear with the paper "Novel low-energy neutral atom imaging technique" in this issue.



Darrell L. Judge received his PhD in physics from the University of Southern California (USC) in 1965. He has been an industrial and government consultant since 1960 and a physics professor at USC since 1965. Beginning in 1977 he has held the position of director of the USC Space Sciences Center. His primary research interests are in laboratory atomic and molecular physics and space physics.

James A. R. Samson earned a BSc from Glasgow University and an MS and PhD from the University of Southern California. He is the author of numerous papers and a text dealing with basic atomic and molecular physics and the interaction of VUV radiation with matter and past editor of the *Journal of the Optical Society of America*. Currently he is Regents' Professor of Physics at the University of Nebraska.

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Nuclear Instruments and Methods in Physics Research A 347 (1994) 472–474
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An optics free spectrometer for the extreme ultraviolet

D.L. Judge [a], M.D. Daybell [a], J.R. Hoffman [a], M.A. Gruntman [a], H.S. Ogawa [a,*], J.A.R. Samson [b]

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The optics-free spectrometer is a photon spectrometer. It provides the photon spectrum of a broadband source by converting photons of energy E into electrons of energy E', according to the Einstein relation, $E' = E - E_i$. E_i is the ionization threshold of the gas target of interest (any of the rare gases are suitable) and E is the incoming photon energy. As is evident from the above equation, only a single order spectrum is produced throughout the energy range between the first and second ionization potentials of the rare gas used. Photons with energy above the second ionization potential produce two groups of electrons, but they are readily distinguished from each other. This feature makes this device extremely useful for determining the true spectrum of a continuum source or a many line source. The principle of operation and the laboratory results obtained with a representative configuration of the optics-free spectrometer are presented.

1. Introduction

The Optics Free Spectrometer (OFS) for the Extreme UltraViolet (EUV) uses the ionization of a rare gas target atom to convert photons whose energy is to be determined into electrons, and then uses electron-energy-analysis techniques to measure the energy of the electrons [1–6]. The photon energy spectrum is then straightforwardly obtained from the electron energy spectrum by simply adding the well-established ionization energy of the target atom (Table I) to the measured energy of the photoelectron.

It is particularly important to note that there are no optical elements which can degrade in this system, nor are there higher-order spectra to untangle from the first-order spectrum, an ever present problem when grating instruments are used for spectroscopy in the EUV wavelength region. Further, to secure long-term stability, it is only necessary to maintain a known gas pressure and to count electrons reliably. The stability of this instrument is limited only by the possibility of time-dependent secondary emission of the electron detector. This possibility can be obviated by post-acceleration of the analyzed photoelectrons which impinge upon the electron detector (channeltron). Further, since this is a pulse counting system, the gain of the detector can be set a factor of 100 or more above the counter threshold so that it will be insensitive even to significant gain changes [7]. The stability makes this device highly desirable in any environment where it is not possible to have ready access to an instrument for exchange of critical elements or where recalibration is inconvenient or problematic. A summary of the advantages and applications of an OFS EUV spectrometer is presented in the last section of this paper.

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2. Experimental apparatus and method

A schematic view of our OFS is shown in Fig. 1. The photons enter from the right through a series of slits ahead of a small ionization volume, or gas box, located above an electron lens. Behind the gas box, on the left, is a light trap. The ion coincidence channel shown above the gas box is an enhancement which lets us sweep out and detect the ion created in the same photoionization event which produced the electron. This feature allows us to eliminate background events, and to monitor the absolute sensitivity of the OFS. Implementation of this enhancement will further improve the already high quality data shown in Fig. 2.

One enhancement not shown in the schematic, but already implemented, is the magnetic shielding required to screen out the Earth's field. The absence of such shielding is known to restrict the wavelength region of OFS operation to wavelengths shorter than 400 Å. We hold the field in our spectrometer to about 1 mG, thus permitting high count rate spectral data to be obtained throughout the rare gas ionization region ($\lambda \leqslant 1024$ Å).

The flow of target gas out of the gas box region is constrained by the slits along the incoming photon beam, and by the small slit on the bottom of the gas box connecting it with the electron lens. The gas pressure is 10–50 μm and gas consumption is small. The five element electron lens allows escaping target gas to be removed from the path of the electrons being analyzed.

Photoelectrons exiting the bottom slit are imaged on the entrance slit of a hemispherical plate electrostatic energy analyzer and electrons of the chosen energy come to a focus at its exit slit. After passing through this slit they are detected by a channeltron electron multiplier. The electron energy spectrum is obtained by sweeping the potentials

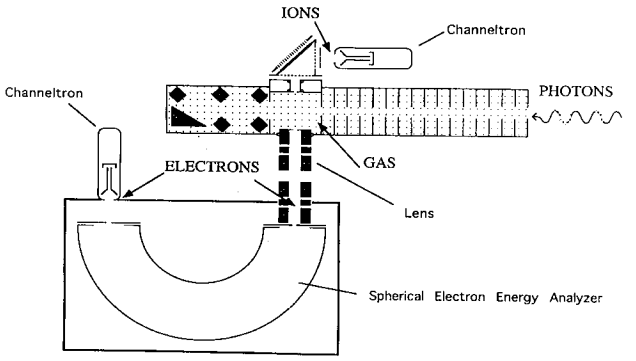

Fig. 1. Schematic diagram of the Laboratory OFS using an electron lens, a spherical electrostatic electron energy analyzer and a channeltron electron multiplier. Also shown is an optional channel to detect the coincident photoion.

applied to the lens-analyzer system and monitoring the count rate from the channeltron.

3. Experimental results

An example of the quality of the data obtained with our OFS is demonstrated in Fig. 2. This figure shows the photoelectron spectrum produced by a helium glow discharge. Here the $n = 2 \rightarrow 1$ (584 Å), $3 \rightarrow 1$ (537 Å) and $4 \rightarrow 1$ (522 Å) transitions are clearly visible. This spectrum was obtained using argon as the target gas in which the electron–ion pairs were produced. In this emission spectrum, the 178 meV splitting associated with the two ionization states of the argon target is clearly resolved. The absence of any significant stray electron background should also be noted.

Except for helium, each of the rare gases that might be used as a photoionization target may be left in one of two

Table 1
Parameters of the rare gases

Gas	Shell	Z	Ionization potential (eV)		$\lambda_{threshold}$ (Å)	
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ionized states with nearly the same energy. This leads to a pair of photoelectron peaks for each incident photon wavelength, as seen in Fig. 2 for an argon target ionized by the 584 Å line from a helium lamp. Using an advanced deconvolution algorithm based on that of Allen and Grimm [8], and taking the "instrument function" to be the experimental response to the sharp, isolated 584 Å emission line, it is possible to transform the doublet output trace of the OFS into a very good replica of the input spectrum. This has been done and is shown in Fig. 3 using a high-sensitivity vertical scale for the resonance series of helium discussed earlier. Notice that the doublet structure in the output trace has disappeared. Also the effective resolving power appears to have improved significantly.

4. Advantages and applications of the OFS

The OFS includes a number of advantages which make it suitable for a wide variety of applications. It is stable over time in the presence of ultraviolet radiation as opposed to conventional grating spectrometers. No second or higher order spectra are present to overlap the spectrum of interest and the instrument is insensitive to wavelengths

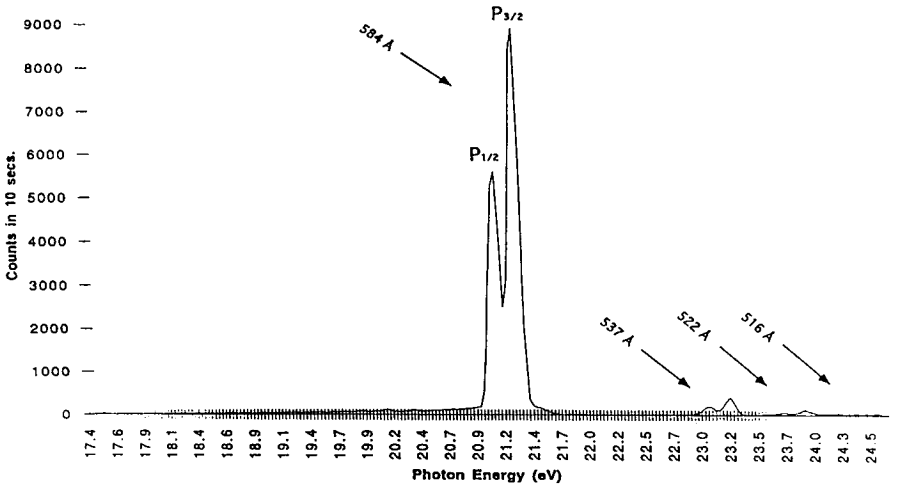

Fig. 2. Photoelectron spectrum produced by a helium microwave glow discharge source illuminating an argon target gas.

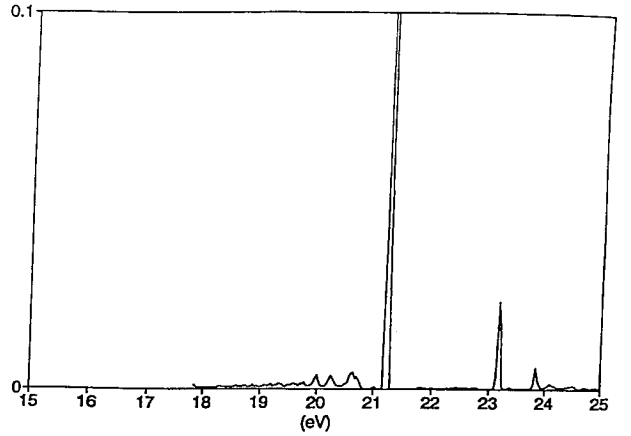

Fig. 3. Deconvolution of the photoelectron spectrum shown in Fig. 2. The vertical scale has been set by normalizing the height of the main peak (the 584 Å He I line) to 1.0.

longer than 1022 Å. If the ion coincidence channel is included, the OFS can be self-calibrating. Stray light effects are small and can be checked by empty target background runs. Saturation of the detector can be avoided by lowering the target gas density, resulting in a large dynamic range. (The lack of a large dynamic range is a particular problem with grating EUV spectrometers using a microchannel plate at their focus to detect a range of spectral lines.)

For solar EUV studies, the OFS technique can provide spectrally-resolved data and reliable relative intensity data for very long periods of time (e.g., years). In addition to supporting planetary atmosphere modeling studies (which require accurate incoming solar flux to evaluate theoretical predictions), the solar EUV flux is a crucial input parameter in obtaining a measurement of the flux of incoming interstellar neutrals by detecting ions created from these neutrals by solar EUV photons. This type of data would also be used in a proposed remote sensing experiment (from an orbiting satellite) to probe the surface composition of bodies lacking an atmosphere. The proposal relies on detecting Auger electrons ejected from surface atoms by EUV and X-ray photons from the sun, and requires a knowledge of the intensity of the solar spectral line responsible.

In EUV spectroscopy using (continuum) synchrotron radiation, the lack of multiple orders is especially valuable, and this may become one of the most important uses of the OFS.

There are also applications of the OFS in plasma diagnostics in which the plasma source would damage the grating of a conventional spectrometer and hence compromise data interpretation. Any kind of laboratory experiment in which the use of an intense EUV discharge light source or the presence of a reactive or dirty specimen causes rapid deterioration of a grating's surface could benefit by use of the method proposed here. Similar arguments apply for many hostile or inaccessible environments such as space flight missions where access to the instrument is not possible and stability is a requirement. For example, thermonuclear blast EUV spectral analysis or near-sun observations from inside the orbit of Mercury are particularly difficult to achieve reliably using conventional spectrometers.

The OFS will find further use where there is a need for a secondary detector calibration standard. The OFS is fundamentally stable because of its lack of a grating and its low sensitivity to detector gain changes. It is also a wavelength sensitive, order-sorting, photon detector with a wide dynamic range (controlled by the pressure of the working gas). Users of bright continuum and line EUV light sources will be able to avoid the difficult and time-consuming spectral analysis required when using conventional spectrometers with multiple order contamination.

Acknowledgements

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